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On the robustness of estimates of mechanical anisotropy in the continental lithosphere: A North American case study and global reanalysis

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ABSTRACT

Lithospheric strength variations both influence and are influenced by many tectonic processes, including orogenesis and rifting cycles. The long, complex, and highly anisotropic histories of the continental lithosphere might lead to a natural expectation of widespread mechanical anisotropy. Anisotropy in the coherence between topography and gravity anomalies is indeed often observed, but whether it corresponds to an elastic thickness that is anisotropic remains in question. If coherence is used to estimate flexural strength of the lithosphere, the null-hypothesis of elastic isotropy can only be rejected when there is significant anisotropy in both the coherence and the elastic strengths derived from it, and if interference from anisotropy in the data themselves can be plausibly excluded. We consider coherence estimates made using multitaper and wavelet methods, from which estimates of effective elastic thickness are derived. We develop a series of statistical and geophysical tests for anisotropy, and specifically evaluate the potential for spurious results with synthetically generated data. Our primary case study, the North American continent, does not exhibit meaningful anisotropy in its mechanical strength. Similarly, a global reanalysis of continental gravity and topography using multitaper methods produces only scant evidence for lithospheric flexural anisotropy.

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1. Introduction

In what are arguably the two most important textbooks published on the subject of flexure and isostasy, neither Lambeck (1988) nor Watts (2001) devotes much space to the question of whether the flexural elastic response of the lithosphere might be directionally (azimuthally) anisotropic, and this despite some early evidence (Stephenson and Beaumont, 1980; Stephenson and Lambeck, 1985; Lowry and Smith, 1995) predating the publication of these works. On the other hand, azimuthal anisotropy is hardly ever absent from a discussion of the seismic signature of lithospheric deformation (Silver, 1996; Montagner, 1998; Park and Levin, 2002), and even very long-term, viscous, anisotropy (Honda, 1986; Christensen, 1987; Lev and Hager, 2008; Tommasi et al., 2008; Hansen et al., 2012) enjoys moderate but sustained attention from modellers and experimentalists alike.

The long-term ($>$1 Myr) flexural strength of the lithosphere is commonly measured in terms of an effective elastic thickness, T_e, which is related to the rigidity, D, of a perfectly elastic plate by

$$D = \frac{ET_e^3}{12(1-\nu^2)}, \tag{1}$$

where E is Young's modulus and ν is Poisson's ratio, both generally assumed to be constant throughout the lithosphere. In reality, the long-term strength of the lithosphere is a combination of brittle, elastic, and ductile strength; in the case of the continental lithosphere, the compositionally distinct upper crust, lower crust, and lithospheric mantle may each include all three regimes (e.g., Burov and Diament, 1995; Burov, 2010). Rather than corresponding to any specific isotherm or compositional boundary, T_e measures the combined effect of this complex rheology by analogy with a purely

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elastic plate, whose thickness represents the integrated strength (e.g., Burov, 2010).

Anisotropy in the elastic behaviour is not easily measured; it is difficult to separate from the complexity of resolving the isotropic elastic response. The latter may be estimated using a variety of methods, including forward modelling of seismic (e.g., Watts et al., 1985) or topography and gravity (e.g., Watts et al., 1980) profiles, but continental-scale studies of spatial variation in T_e are most commonly performed via cross-spectral analysis of topography and gravity anomalies (e.g., Dorman and Lewis, 1970; McKenzie and Bowin, 1976; Watts, 1978; Forsyth, 1985), which usually involves admittance or coherence functions. A variety of statistical devices, such as windowing and tapering, are called upon to diminish the bias and reduce the variance of the estimates (e.g., Ojeda and Whitman, 2002; Crosby, 2007; Kalnins and Watts, 2009; Pérez-Gussinyé et al., 2009). However, the reduction of hundreds of gravity and topography data points to admittance or coherence estimates at a handful of statistically uncorrelated wavenumbers results in a loss of statistical efficiency, limiting the potential of admittance- and coherence-based T_e estimates, however well carried out (Simons and Olhede, 2013).

Nevertheless, after the early works cited, increased attention led to the development of a suite of methods to locally extract directional anisotropy in the effective elastic thickness (Simons et al., 2000, 2003; Swain and Kirby, 2003a; Audet and Mareschal, 2004; Kirby and Swain, 2006). First applied to the Australian continent and the Canadian Shield, these methods have since yielded apparent evidence for pervasive mechanical anisotropy worldwide (Rajesh et al., 2003; Stephen et al., 2003; Nair et al., 2011, 2012; Zamani et al., 2013).

Audet and Bürgmann (2011) made a geologically attractive case for tectonic inheritance being a controlling factor in the deformation behaviour of the lithosphere throughout supercontinent cycles. Their analysis, like that of Simons et al. (2000), relied on the identification of weak directions with azimuths where the coherence between Bouguer gravity anomalies and topography exceeds the isotropic average. Finding examples of such anisotropy in the continents worldwide, Audet and Bürgmann (2011) then showed its correlation with lateral gradients in the isotropically-estimated elastic thickness, which are often aligned perpendicular to tectonic boundaries.

In this paper we draw attention to the “lingering problems” and “unresolved question[s]” identified by Audet (2014), indeed, to the general difficulty of inferring lithospheric anisotropy from gravity–topography coherence. We specifically formulate our own concerns that a great many of the “weak” directions marked in Fig. 1 of the paper by Audet and Bürgmann (2011)—and by implication, in the results of most other workers including some authors of this present study (e.g., Simons et al., 2000, 2003; Kirby and Swain, 2006)—may in fact be spurious artefacts due to the statistical properties of the analysis method.

2. Method and motivation

The coherence γ^2 is a normalised cross-power spectral density S of topography H and gravity G,

$$\gamma^2_{GH}(\mathbf{r},\mathbf{k}) = \frac{|S_{GH}(\mathbf{r},\mathbf{k})|^2}{S_{GG}(\mathbf{r},\mathbf{k})S_{HH}(\mathbf{r},\mathbf{k})}, \tag{2}$$

where $\mathbf{r}$ is the spatial-domain position vector and $\mathbf{k}$ the spectral-domain wave vector. It is a statistical measure of the average wavelength-dependent relation between two multivariate fields (Bendat and Piersol, 2000). That it contains information about the isostatic or flexural compensation mechanism by which to estimate the variable strength of the lithosphere is not in question here (but see Simons and Olhede, 2013). However, the identification of directionally anisotropic behaviour in the estimated coherence between gravity and topography — a methodology that one of us is at least partly responsible for promoting (Simons et al., 2000, 2003) — is not sufficient indication of intrinsic anisotropy in the mechanical process linking both geophysical fields (Swain and Kirby, 2003a; Kirby and Swain, 2006).

Two further basic ingredients are necessary for the conclusion that lithospheric strength behaves anisotropically, i.e., differently depending on the look direction (azimuth). Firstly, it is necessary to establish that the directional variations of the coherence at a given constant wavenumber are robust and statistically significant with non-negligible probability. They should not arise by chance under a null-hypothesis of intrinsically isotropic behaviour, as could be due, for instance, to spectral discretisation effects or when anisotropic initial loads are emplaced on an isotropic lithosphere. Secondly, any robust variations in the coherence must lead to significant anisotropic variations in the parameter of interest, namely, the lithospheric flexural rigidity, which is derived from it by an inversion that is subject to its own, potentially large, estimation uncertainty.

As to the first requirement, it should be shown that when no lithospheric anisotropy is in the system, none is introduced by the analysis. As to the second, the inferred directionally dependent values of elastic strength need to be evaluated against the uncertainty with which the isotropic elastic strength can be determined from the same data. Such a statistical analysis will need to be tailored to the method used to determine the coherence, whether via multitaper spectral analysis, wavelets, or any other method. We can thus greatly reduce spurious identifications via statistical tests on the coherence, on the results of the rigidity estimation, and finally, by testing that it is not simply the widespread spectral anisotropies of gravity or topography themselves which impart insufficiently informative anisotropy to the coherence, or apparent anisotropy to the rigidity estimated from their relation.

In order to explore how widespread spurious anisotropy measurements may be in published studies, we have chosen to test two methods commonly used (with variants) over the last fifteen years: the Slepian-windowed multitaper method (duration × half-bandwidth product $NW = 3$, Shannon number 6, using 4 tapers in each dimension) of Simons et al. (2000) and the fan-wavelet method (Morlet wavelet with central wavenumber $k_0 = 5.336$) of Kirby and Swain (2006, 2011), which is the basis of the fan-wavelet method of Audet and Mareschal (2007). For simplicity, we use square data patches or windows. Selective methods for regions of arbitrary description, such as irregular tectonic provinces, have also been developed, and may help avoid blending contrasting T_e from different features into a single estimate (Simons and Wang, 2011). However, most workers to date have used square or circular windows, making a simple geometric patch a better test domain for the reliability of existing analyses.

There are a great many subtleties involved in “inverting” a coherence curve for a proper estimate of the effective elastic thickness, including the choice of Bouguer versus free-air gravity anomalies (McKenzie and Fairhead, 1997; Banks et al., 2001; McKenzie, 2003; Swain and Kirby, 2003b; Pérez-Gussinyé et al., 2004). The difficulties are especially daunting in the presence of correlation (r) between surface and subsurface loading (Macario et al., 1995; McKenzie, 2003; Kirby and Swain, 2009), which are furthermore present in an unknown proportion of variance to each other, the loading ratio (f^2), which may be wavenumber-dependent (Simons and Olhede, 2013). We point to the comprehensive overviews and historical reviews by Simons and Olhede (2013) and Kirby (2014) for more context. Here, for the multitaper method, we use the simple coherence transition-wavelength metric to determine relative values of effective elastic thickness

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